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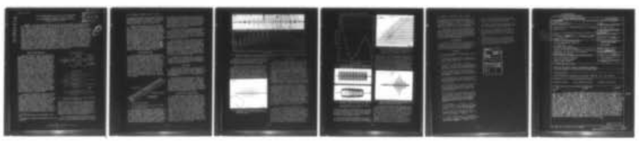

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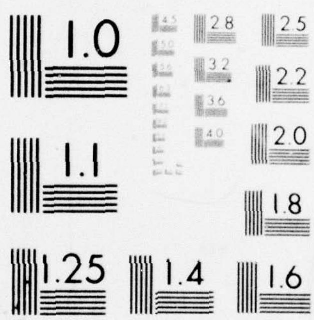

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REFLECTIVE-ARRAY MATCHED FILTER FOR A 16-PULSE RADAR BURST*

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ABSTRACT. A new type of matched filter has been designed and fabricated for a doppler-sensitive burst waveform with 16 equally spaced linear-FM subpulses, each of which has a 60MHz bandwidth and is 3 μs long. The interpulse period is 5 μs, and the total duration of the waveform is 80 μs. The filter consists of 16 reflective-array-compressor sections ion-beam etched in the surface of a 15.2-cm-long Y-Z $LiNbO_3$ substrate. The reflective-array section for each subpulse is depth-weighted according to a Hamming function for range-sidelobe suppression, and the peak responses of successive sections have a Hamming weighting for doppler-sidelobe suppression. A reduction of system complexity and an improvement in dynamic range is expected with filters of this type as compared to conventional doppler burst processors. We have fabricated on one substrate a matched filter for an entire burst, thus providing the full correlation gain inherent in the waveform within a single device. This yields a large dynamic range despite a relatively high insertion loss (43 dB CW at center frequency (200 MHz) for the central section). Within a given section, the phase deviations from quadratic are typically 5^o r.m.s. and corresponding range sidelobes are more than 30 dB down from the correlation peak. These phase deviations and the errors in delay between sections can be reduced by metal overlay patterns. A filter for the zero-doppler channel was built to operate at a temperature of 60^oC. When the temperature is changed by 0.98^oC, the peak response of this filter is shifted by an amount equal to the doppler resolution (18 kHz). Thus by operating a number of nominally identical devices at a series of temperatures separated by 0.98^oC, a complete doppler processor can be obtained.

Doppler Signal Processing

Range and velocity of targets are standard parameters measured by radars. Radar waveforms which are employed to simultaneously measure range and velocity often consist of a train of linear-FM subpulses[1,2]. This is referred to as a burst waveform. When such a waveform is reflected from a moving target, the doppler effect will contract the time between the subpulses in the reflected signal because the range will have shortened in the time interval between reflection of successive subpulses. The radar-signal-processing task is to measure the amount by which the subpulse spacing contracts and thus determine target velocity. A straightforward method for accomplishing this is to employ a bank of devices each of which is a matched filter for a radar return from a target traveling at a particular velocity. A bank of such filters will span the velocities of interest. Each filter has an impluse response which is the same as the transmitted waveform except that the time interval between subpulses within the impulse response of each filter is matched to a particular target velocity. Velocity or doppler filtering results because if the return from a target with one velocity is processed by a filter matched to a different velocity, the responses from each subpulse will not add in phase, thus reducing the correlation peak. This paper describes a technique for achieving such matched filters.

A conventional technique for effectively creating a bank of filters and thereby processing burst waveforms is illustrated in the upper portion of Fig. 1. A pulse compressor processes each subpulse in sequence. The compressed pulses are sent into a delay line with N taps which are spaced by the delay T_0 between the N subpulses in the transmitted waveform. The N separate outputs are then sent into the doppler processor or velocity correlator. This device sums its N inputs with proper phase factors to yield at each of the M output ports an overall response which is the matched filter for a particular velocity. The main difficulty with the conventional approach is that the

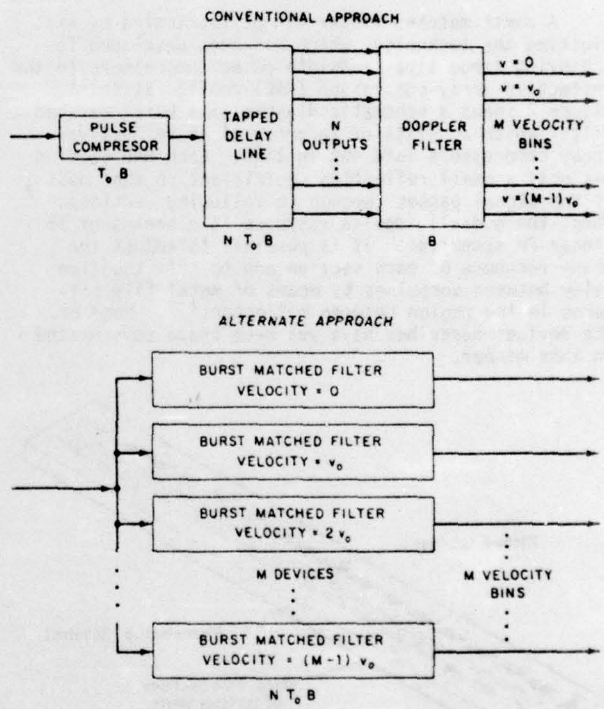

Fig. 1 Techniques for doppler processing of N-subpulse waveforms with bandwidth B.

tapped delay line must span the full time NT_0 and bandwidth B of the waveform and provide N separate outputs each with carefully controlled amplitude and phase[3,4]. However, the delay line has a correlation gain which is only a factor of N. This means that the device must have relatively low CW insertion loss in order to obtain adequate dynamic range as a matched filter. In addition, the doppler filter is a complex device in which precise phase relations between the N inputs and M outputs are required over a wide bandwidth[1,2].

The alternate approach shown in the lower portion of Fig. 1 is the straightforward technique of providing a separate matched filter for each velocity of interest.

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In this case, the matched filter has the same time NT_0 and bandwidth B as the transmitted waveform, but also has the full correlation gain of $NT_0 B$, so that only a modest CW insertion loss is required in order to achieve a high dynamic range as a matched filter.

A bank of burst matched filters can be created from a number of nominally identical devices in two ways. In one case, the separate inputs to a number of identical devices would be derived by mixing the radar return with a series of local oscillators each offset from the reference oscillator by an amount equal to the appropriate doppler frequency shift. Alternatively, identical devices can be fabricated on substrates for which the internal delay is a function of temperature. By operating such devices at various temperatures, they could be matched to particular velocities. For the device described herein, the doppler resolution is 18kHz, corresponding to a velocity resolution of 900 m/s in a3-GHz radar. The filter on $LiNbO_3$ operates at an I.F. of 200 MHz. A shift in device response equal to the doppler resolution can be affected by a 0.98°C change of the substrate temperature. This degree of control is achievable with commercial ovens.

Burst Matched Filter

A burst matched filter can be fabricated by exploiting the technology which has been developed for achieving large time-bandwidth pulse compressors in the reflective-array-compressor (RAC) configuration[5-9]. Figure 2 shows a schematic diagram of a burst matched filter which consists of an array of 16 reflective-array compressors laid out in line. Each RAC section has only a small reflection coefficient so that most of the signal passes through to following sections. Thus, the overall impulse response is a series of 16 linear-FM subpulses. It is possible to adjust the phase response of each section and to trim the time delay between subpulses by means of metal film patterns in the region between reflectors[7-9]. None of the devices described have yet been phase compensated in this manner.

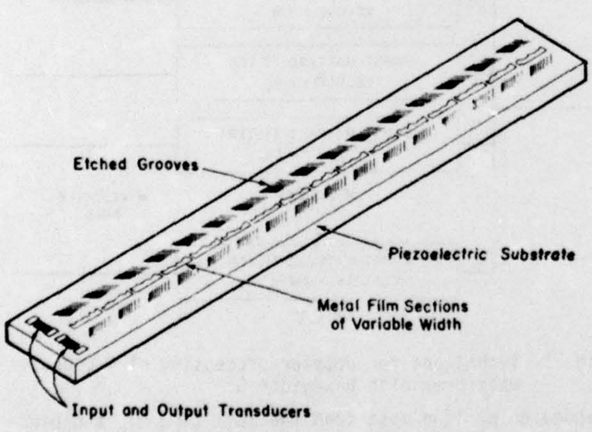

Fig. 2 Burst matched filter consisting of 16 reflective-array sections.

The burst matched filter contains two types of amplitude weighting. Each subpulse is Hamming weighted for range sidelobe suppression and the magnitudes of successive subpulses are Hamming weighted for doppler sidelobe suppression. This weighting was accomplished by varying the depth of the grooves in the grating[10,11]. The input and output transducers contributed some spectral weighting. The desired groove depth as a function of position was determined by a model[11,12] which included the reflection and transmission characteristics of each grating section, propagation loss, and transducer response. Groove depths in the model were adjusted to provide the desired weighting. A device fabricated according to this prescription yielded an amplitude response with a maximum deviation from the desired value of less than 3 dB. An empirical iteration of the depth profile provided a second device with nearly ideal amplitude response.

A significant feature of the geometry illustrated in Fig. 2 in that the folded propagation path yields twice the delay of an in-line device. Previous designs[3,4] for achieving 80 μs of delay in a tapped delay line employed a cascade of delay lines. In this case, it is difficult to control phase response and maintain bandwidth in cascaded devices.

The burst matched filter described herein operates at a center frequency of 200 MHz and has a 60-MHz bandwidth. The interpulse period of the 16 subpulses is 5 μs. Each reflective-array section contains 800 grooves spanning 4 μs. The central 600 grooves are weighted to provide Hamming weighting over 3 μs. The remaining 200 grooves on the ends of each section are weighted with cosinusoidal tails for Fresnel-ripple suppression. Each subpulse has a time-bandwidth product (over 3 μs) of 180 and the overall time-bandwidth product of the burst waveform is 4800.

To test the burst matched filter, an expansion line consisting of only one RAC section was also fabricated. In this case, depth weighting was employed to yield a flat amplitude response over a bandwidth of 60 MHz and a dispersion of 3 μs.

Fabrication

The filter was fabricated on a 15.2-cm (six inch) Y-Z $LiNbO_3$ substrate. Input and output transducers were inductor tuned to yield on overall conversion loss (including bidirectionality) of 12 dB. The widths of the transducers and gratings were 100 wavelengths at center frequency.

Because of the high degree of spatial detail required in the profile of groove depths, a relatively small etching aperture was employed[10,11]. The aperture used (500 μm wide) spanned 10% of a section but only 0.4% of the total length of the device. Total etching time for a device is proportional to the ratio of etching aperture to the total length of the device. Ion-beam etching to a typical depth of 0.1 μm over 14 cm. through such a small aperture required 10h. Etching was done in four separate 2.5-hour passes.

Response of Individual Sections

The impulse response of a burst matched filter shows the overall Hamming-on-Hamming weighting of the 16 sections, Fig. 3. The impulse response is clean and free of significant spurious signals. Fig. 4 shows the insertion loss versus frequency for each of the 16 sections. The measured amplitude response follows quite closely the desired Hamming-on-Hamming weighting indicated by the solid line. These measurements were made using CW bursts which were long enough to reach a quasi-CW condition in the output but short enough to resolve the response of each section individually. The minimum insertion loss to the central section is 43 dB. Of this total, the transducers contribute 12 dB. The reflection loss of the central section is 26 dB. The remaining 6 dB of loss is due to energy reflected by preceding sections and to propagation loss. For the pulse expander, deeper gratings (~0.23 μm) yielded a reflection loss of 16 dB and an overall CW insertion loss of 28.5 dB.

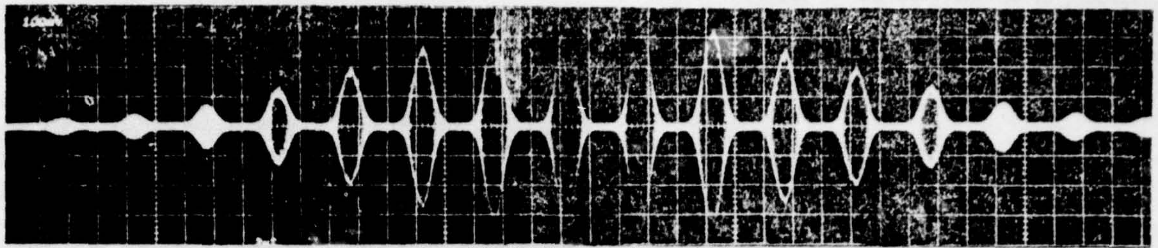

Fig. 3 Impulse response of weighted burst matched filter. Horizontal scale is 2 μs/div.

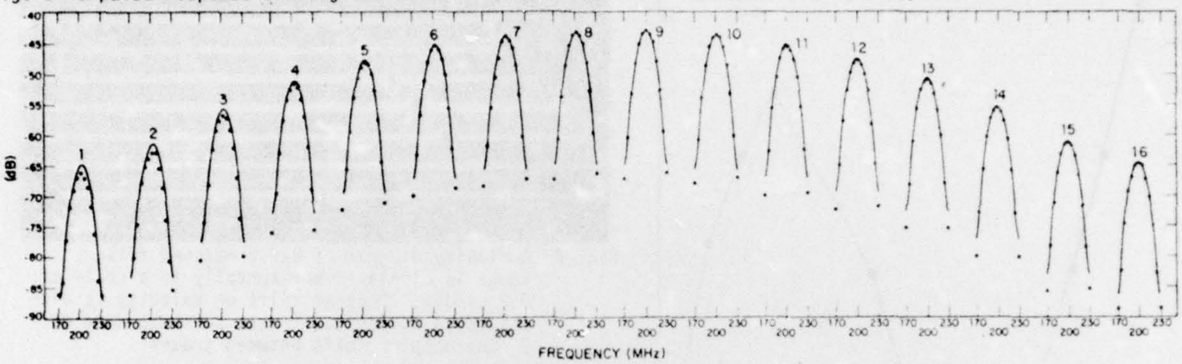

Fig. 4 Frequency response of 16 individual sections. Solid curves are the desired Hamming-on-Hamming weighting. Data points are nomalized to the peak response of section 8.

Measurements of the phase response of each section showed phase deviations from the desired linear-FM response amounting to approximately 5° r.m.s. Most of the errors were slowly varying across the passband.

The pulse-compression performance of each section was evaluated. A single linear-FM subpulse was generated by impulsing the expansion line. When processed by the burst matched filter, 16 compressed pulsed emerge, Fig. 5. Some of the compressed pulses have shoulders on the main lobe at approximately the 20-dB level. All other sidelobes are more than 30 dB below the peak of the corresponding compressed pulse. These results are consistent with the measured phase errors.

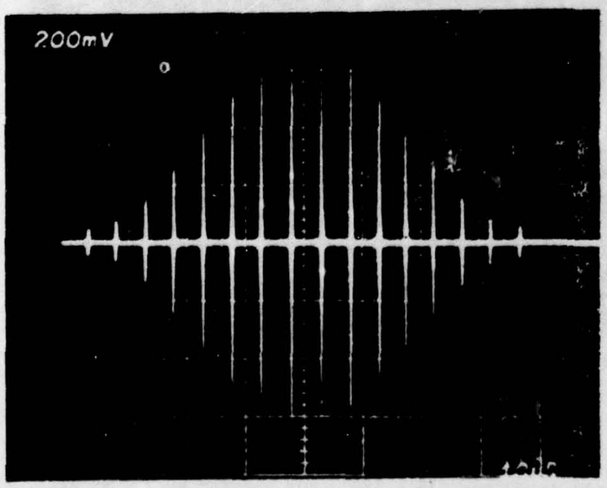

Fig. 5 16 compressed pulses resulting from the excitation of a burst-matched filter by a single linear-FM subpulse.

Burst Processing

The filter is designed to match a periodic burst waveform and therefore the subpulse-to-subpulse delay within the impulse response of the filter should be a constant. Deviations from a constant increment, expressed in degrees of phase at center frequency, are shown in Fig. 6. The phase errors mean that the contributions from each subpulse will not add exactly in phase at the correlation peak. These errors cause a degradation in correlation gain and increased doppler sidelobes. The major source of errors in subpulse spacing is the phase shifts in each RAC section caused by energy storage effects[13,14]. Gratings of different depths contribute different phase shifts on transmission and the cumulative effect is shown in Fig. 6. In subsequent devices it will be necessary to use phase compensation patterns to adequately reduce these errors.

A coherent burst waveform of 16 linear-FM subpulses was generated in order to test the overall response of the burst matched filter. The waveform was created by deriving 16 coherent impulses from a reference oscillator operating at approximately 200 MHz. These impulses were applied to the pulse expander. The 16 linear-FM chirps thus generated were each gated to 3 μs to form the waveform shown in the upper portion of Fig. 7. The delay pedestal in the pulse expander was established so that any feedthrough of the impulses would occur in the interval between subpulses and thus be gated out. A single subpulse is shown in the lower portion of Fig. 7. A change in the frequency of the reference oscillator results in a change in subpulse spacing. This simulates a doppler shift.

When a burst waveform is processed in a burst matched filter, 31 compressed pulses emerge. The 16th compressed pulse is the correlation peak. The ability of the filter to resolve targets in range and velocity is shown in Fig. 8. In the upper half, a segment in time surrounding the 16th compressed pulse is displayed. Each trace corresponds to a different value of the reference oscillator frequency and thus each trace represents targets at different velocities. Successive traces correspond to an increment of 20 kHz. Each trace has been manually offset both horizontally and

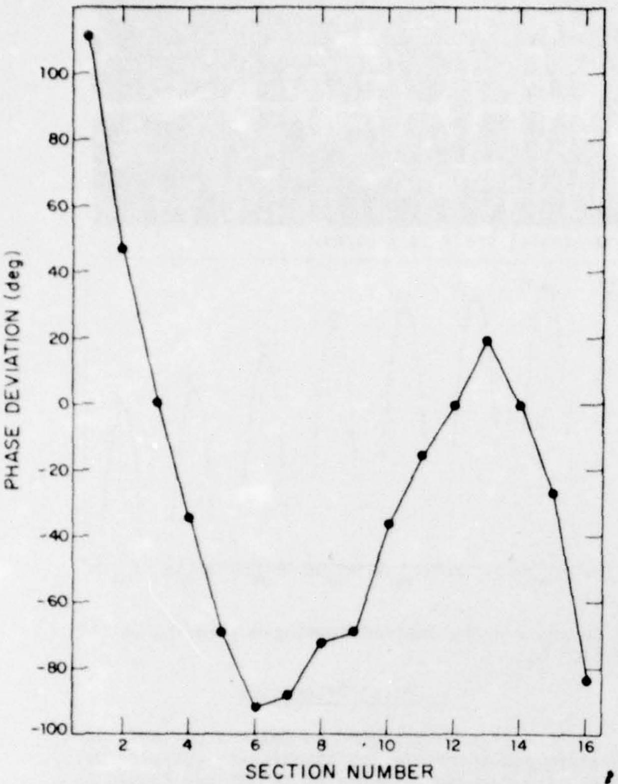

Fig. 6 Phase deviation from constant incremental delay versus section number of burst matched filter measured at 200 MHz.

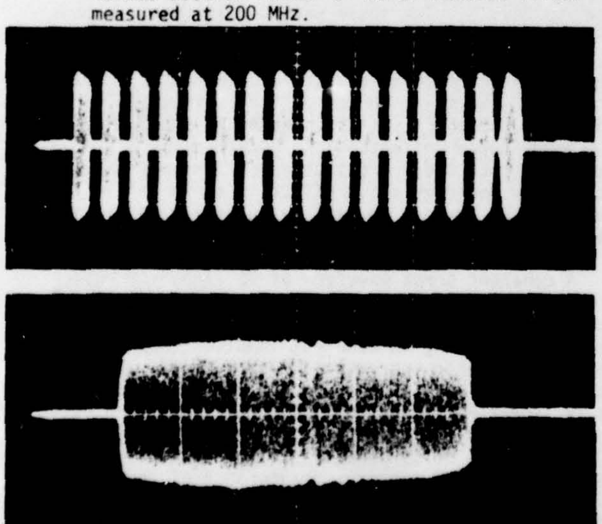

Fig. 7 (a) Burst waveform consisting of 16 linear-FM subpulses. Horizontal scale is 10 μs /div.

(b) Detailed view of one linear-FM subpulse. Horizontal scale is 0.5 μs /div.

vertically in order to provide this display. This type of display shows cuts of the surface of the ambibuity function for the waveform[1,2]. Range (time) sidelobes are typically 30 dB down, consistent with the results observed for single compressed pulses.

In order to evaluate the doppler-sidelobe characteristics of the filter, the amplitude of the peak of the correlation function was measured at each frequency.

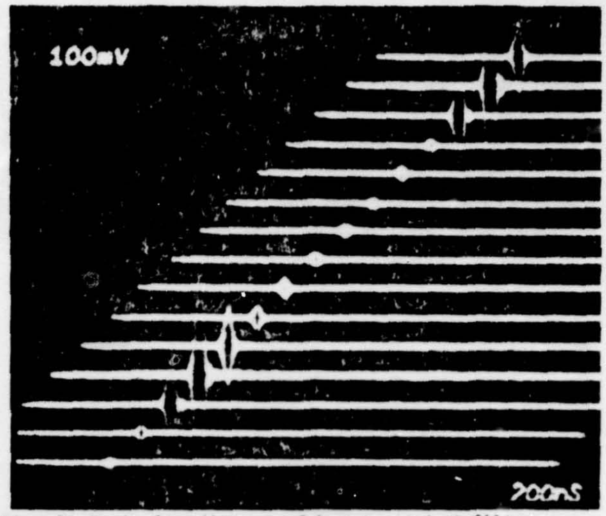

Fig. 8 Ambiguity diagram of burst matched filter. Range is displayed horizontally to a scale of 0.2 μs/div. Doppler shift or velocity is displayed on successive traces corresponding to 20-kHz doppler shift between traces.

The peak values at discrete frequencies separated by 5 kHz are shown in Fig. 9. Measurement at a single frequency creates a single vertical trace in this display. The envelope of the doppler response indicates significant departures from ideal Hamming response. The main pulse is somewhat distorted and the sidelobe levels are only down about 20 dB. These features are directly traceable to errors in the interpulse delay which were discussed previously. Significant improvements can be anticipated when phase compensation is employed.

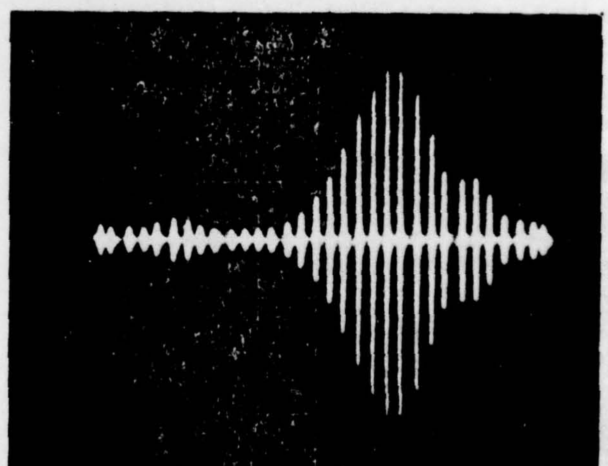

Fig. 9 Details of compressed pulse versus doppler shift. Data was taken at discrete frequencies and displayed on a scale of 20 kHz/div.

A perfect burst matched filter would have a correlation gain equal to the total time-bandwidth product of the subpulses (16 x 180), but reduced by 2.7 dB because of the Hamming-on-Hamming weighting. This yields an ideal correlation gain of 32 dB. The signal loss to the correlation peak can be related to the CW insertion loss. The time-bandwidth product of each subpulse is 180, but the compressed pulses are reduced by 5.3 dB by Hamming weighting. The coherent addition of 16 subpulses (at an average level of 0.54 due to Hamming weighting) yields an overall signal gain of 36 dB relative to the CW insertion loss. The measurements in

Fig. 4 indicate the net insertion loss to the correlation peak should be 7 dB. However, the measured loss is approximately 9 dB. The excess loss is mainly due to errors in subpulse delays, Fig. 6. The relatively low value of insertion loss yields a device with a very large dynamic range, even with modest input power.

In conclusion, the burst matched filter described here illustrates the utility of such a device for velocity discrimination with wideband radar burst waveforms. Even without phase compensation, these devices yield good range sidelobes and fair doppler sidelobes. A bank of phase compensated devices can function as a doppler processor for burst waveforms.

Acknowledgements

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Reflective-array Burst matched filter 16-pulse radar burst

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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